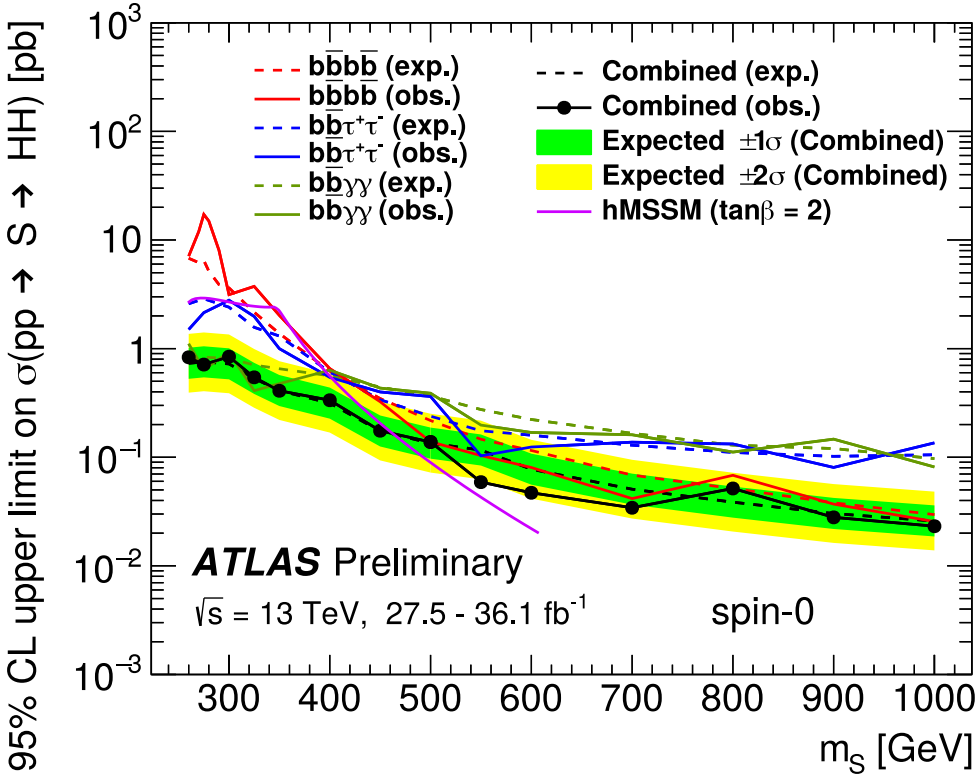
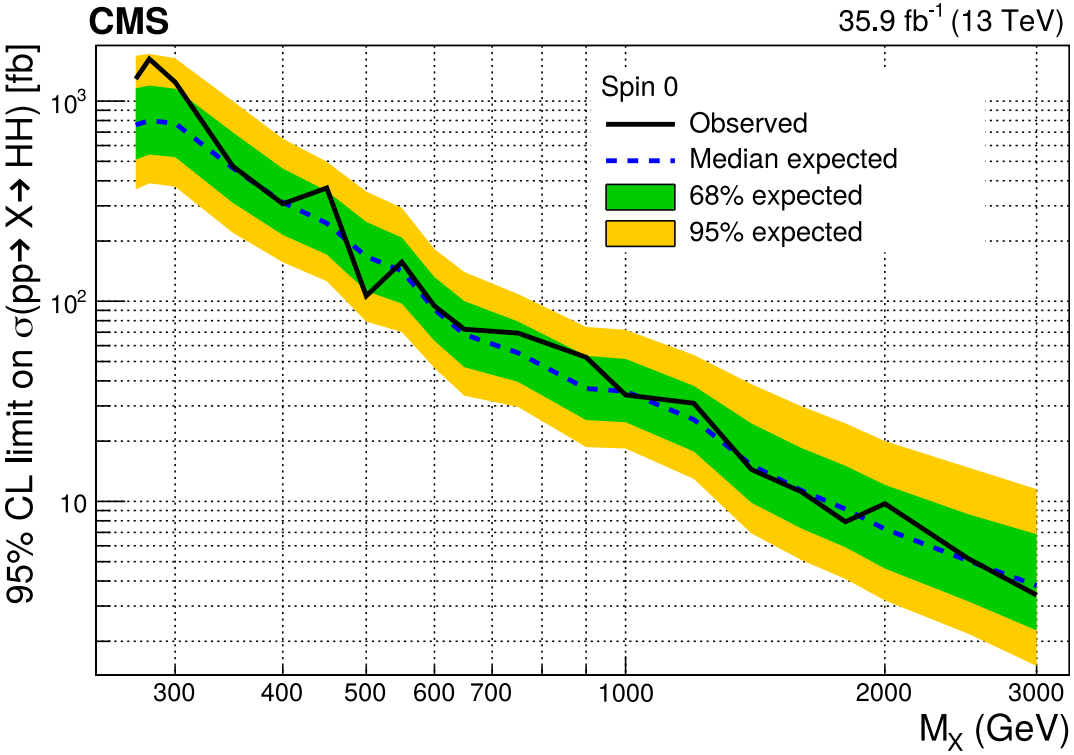
Resonant HH searches by ATLAS and CMS

Andres Tiko (INFN Padova) on behalf of ATLAS and CMS Collaborations

Status of current best results



ATLAS-CONF-2018-043



arXiv:1811.09689

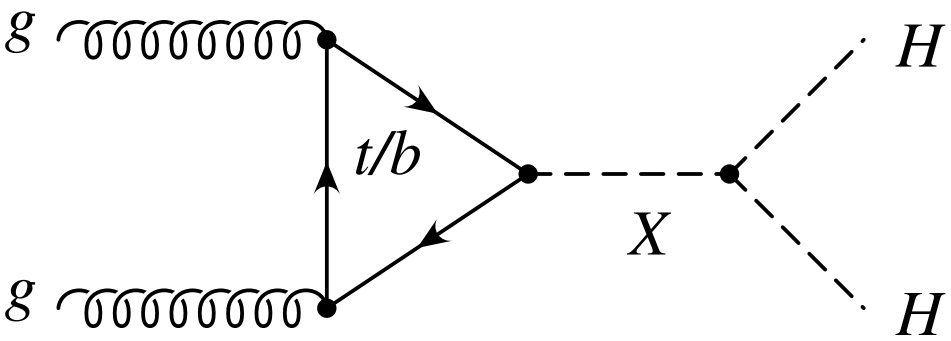
Wide range of masses studied, no excess over background expectation

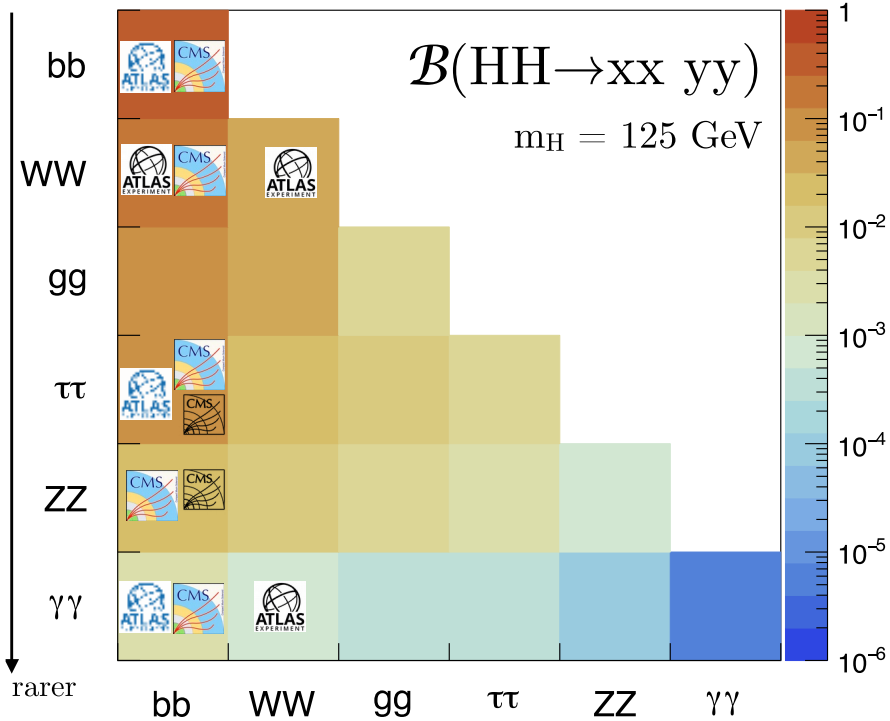
Outline

- **Motivation and theoretical framework**
- **New results**
- **Searches included in combination**
  - $b\bar{b}VV$
  - $b\bar{b}b\bar{b}$
  - $b\bar{b}\tau\tau$
  - $b\bar{b}\gamma\gamma$
- **Combination**
- **Other results**
- **Prospects**

Motivation and framework

- Several **BSM theories predict** the existence of heavy **particles decaying into a pair of Higgs bosons**.
- Various **models explored** with particles decaying to a Higgs boson pair:
  - **Spin-2 graviton**, as predicted in the Randall–Sundrum model of warped extra dimensions
  - **Spin-0 radion**
  - Models with two Higgs doublets (**2HDM**s)
- **Current** studies mostly **focus**ed **on ggF** production mode
- **Many decay channels** provide possibilities for various searches with diverse analysis techniques and sensitivities in different mass ranges
- A **combination** of channels **needed** to obtain the best possible **sensitivity** for the HH production
- Most searches use ≈36 fb^{-1} 2016 or 2015+2016 data





Coloured logos show channels included in combination

New Results

WW(*)WW(*) – ATLAS

Final states of **2SS, 3 and 4 leptons** + **MET** and **jets**

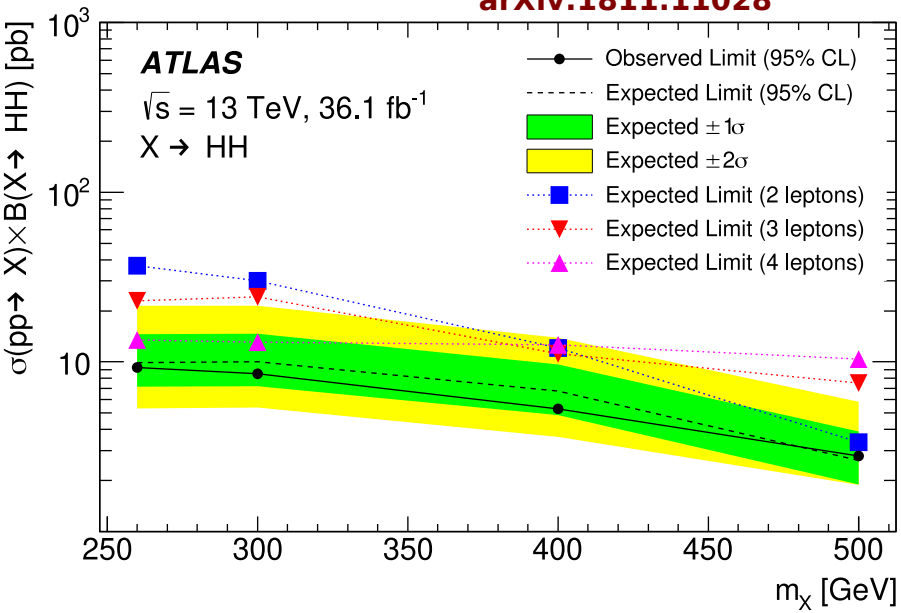
Assumption $m_X > 2m_H$ such that both H are produced on-shell

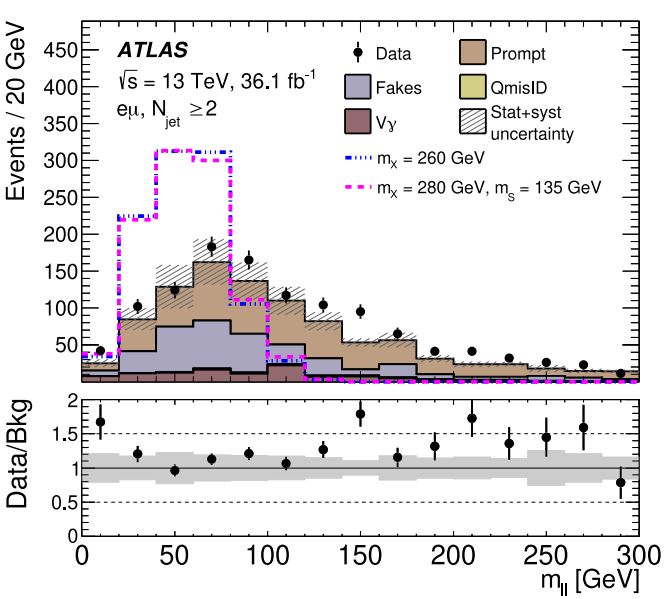
Obs (exp) limits range from **9.3 (10) pb to 2.8 (2.6) pb**, with the smallest limit set for m_X = 500 GeV

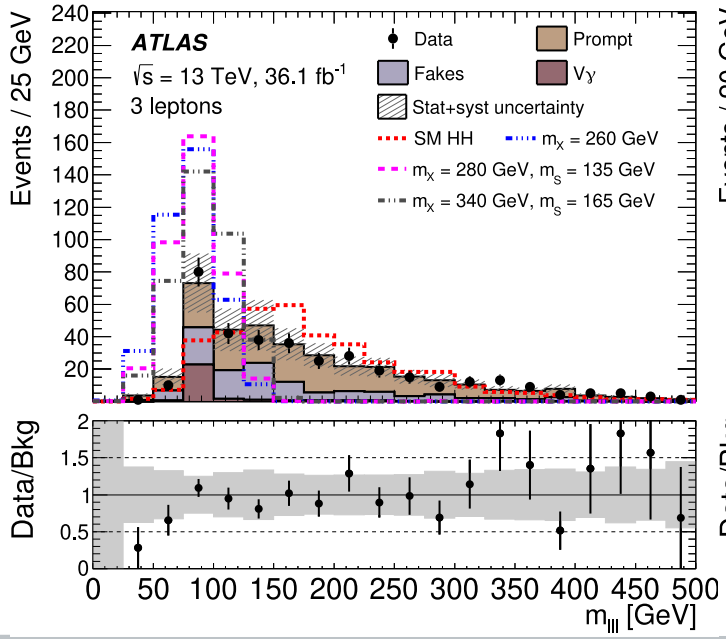
No excess over SM backgrounds found

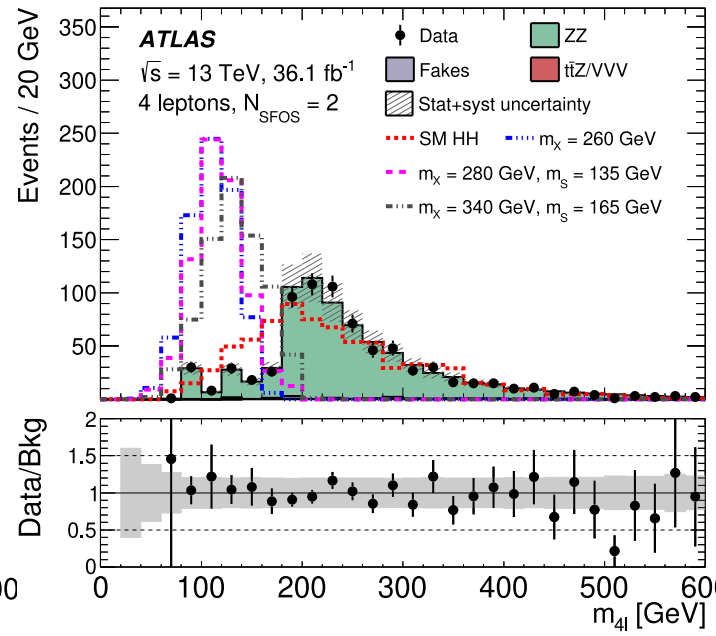
Limits also set **for new scalar bosons** in the process X → SS → WW(*)WW(*)

arXiv:1811.11028

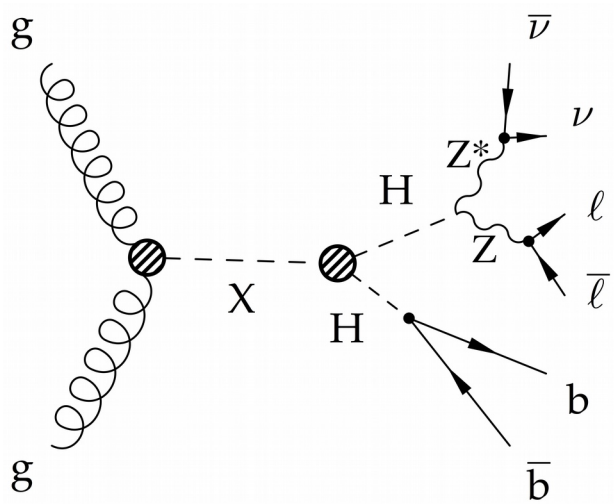


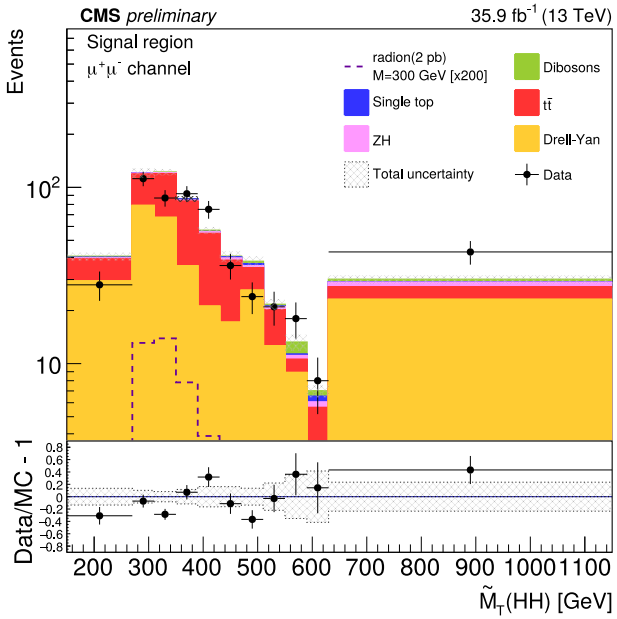






$b\bar{b}ZZ^*$ decays in the $bb\ell\ell\nu\nu$ final state – CMS





On-shell Z boson decays to **e^+e^- or $\mu^+\mu^-$** pairs, **$m_{\ell\ell}$ > 76 GeV** for orthogonality with $b\bar{b}VV$ search

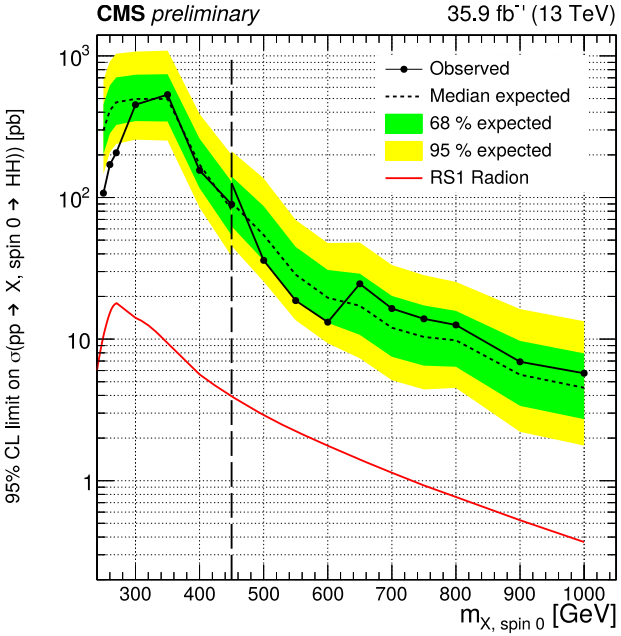
The **other Z** boson can be off-shell, decays **to neutrinos**

Signal and control regions defined using **$m_{b\bar{b}}$** and **$m_{\ell\ell}$**

- Main backgrounds **$t\bar{t}$** and **DY**
- Two **BDTs** trained, above and below m_X = 450 GeV

Limits for radion and graviton by:

- Binned ML fit of the **pseudo-M_T(HH)**
- Simultaneously in the signal and control regions for combined e^+e^- and $\mu^+\mu^-$

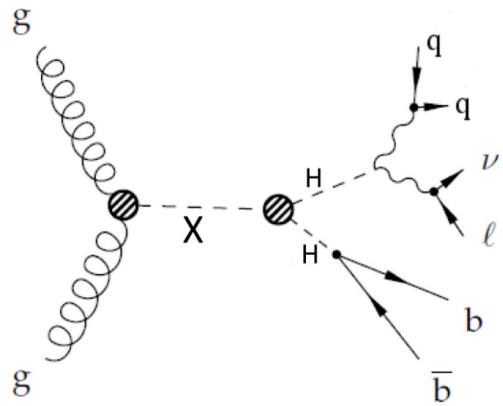


CMS-PAS-HIG-17-032

$b\bar{b}WW$ – ATLAS

Semileptonic decays of WW* considered:

Resolved and boosted modes for H → $b\bar{b}$ decay

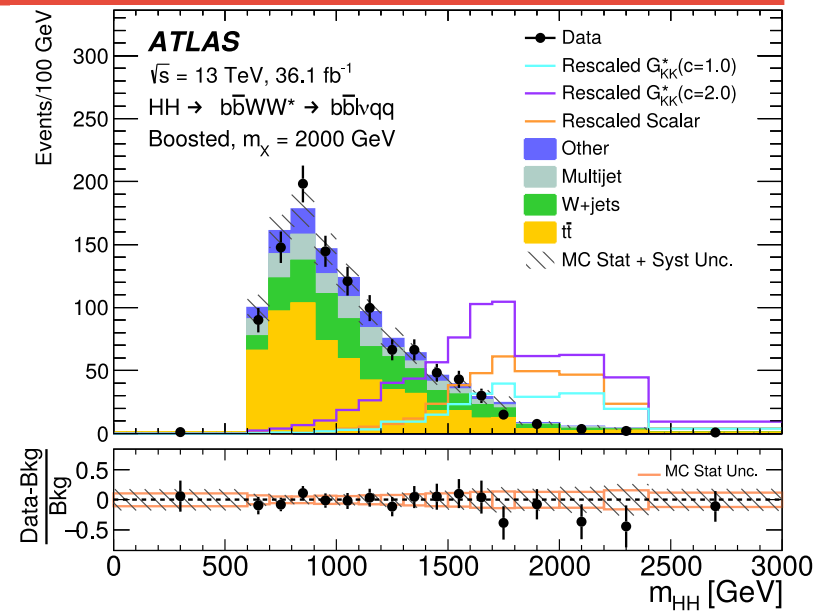


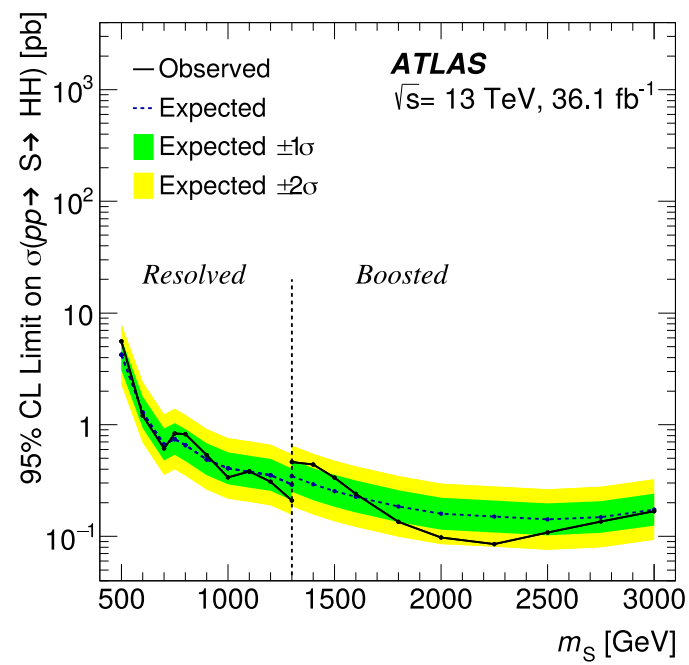
Control regions outside [100, 140] GeV window for $m_{b\bar{b}}$ to **normalize** and validate the estimate of the main **$t\bar{t}$** background

Kinematic selection suppresses $t\bar{t}$ background, **optimized for** a **spin-0** signal, limits also for spin-2

Limits from a **ML fit to** the $\boldsymbol{m_{HH}}$ distribution simultaneously in signal and control regions, with combined **electron** and **muon** channels

No excess over background expectation found





arXiv:1811.04671

Results included in combination

$b\bar{b}VV$ - CMS

Includes two processes:

- **$HH \to b\bar{b}WW \to bbl^+\nu l^-\nu$**
- **$HH \to b\bar{b}ZZ \to bbl^+l^-\nu\nu$**

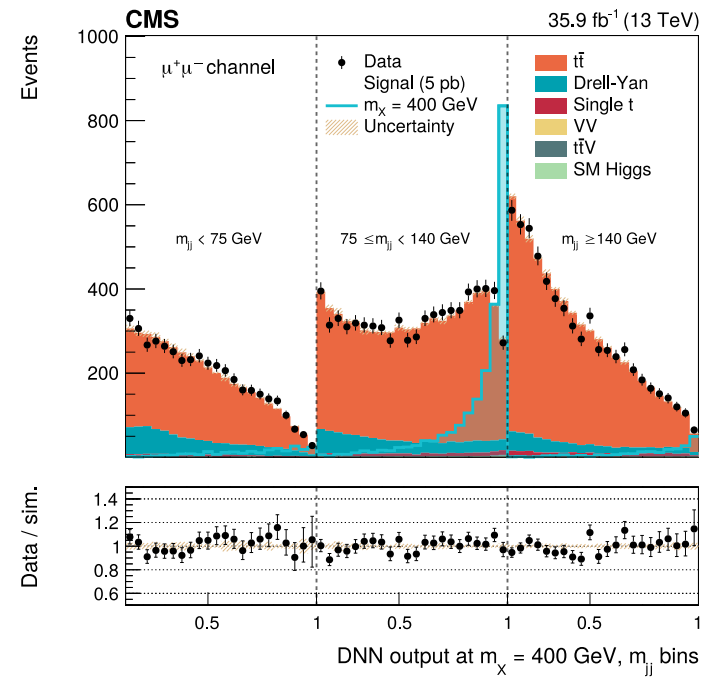
Primary focus on bbWW

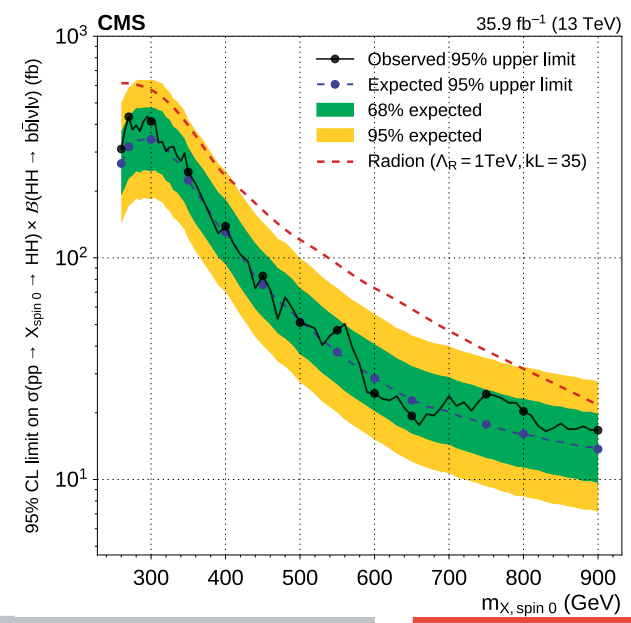
$12 < m_{ll} < m_Z - 15$ GeV cut to suppress backgrounds:

- Negligible impact on $H \to WW$ decays
- Removes the subset of $H \to ZZ$ with on-shell Z(ll), covered by bbZZ analysis shown previously

A **DNN** is used **to** improve **rejection** of large $t\bar{t}$ and DY **backgrounds**, parametrized according to the mass of the resonance

DNN output for ML fit, setting limits



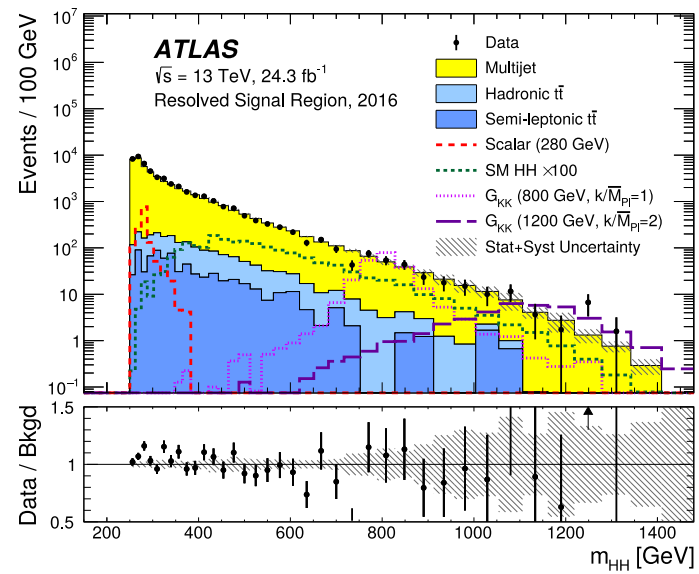


JHEP 01 (2018) 054

$b\bar{b}b\bar{b}$ - ATLAS

Most sensitive channel for ATLAS for high masses

- Predominant **multijet background** estimated **from data**
- **Background normalizations** for multijet and $t\bar{t}$ determined with simultaneous fits in sideband region
- Profile-likelihood fit of $\mathbf{m_{HH}}$ to extract the signal
- **2 analyses**, combined in mass range 800-1400 GeV

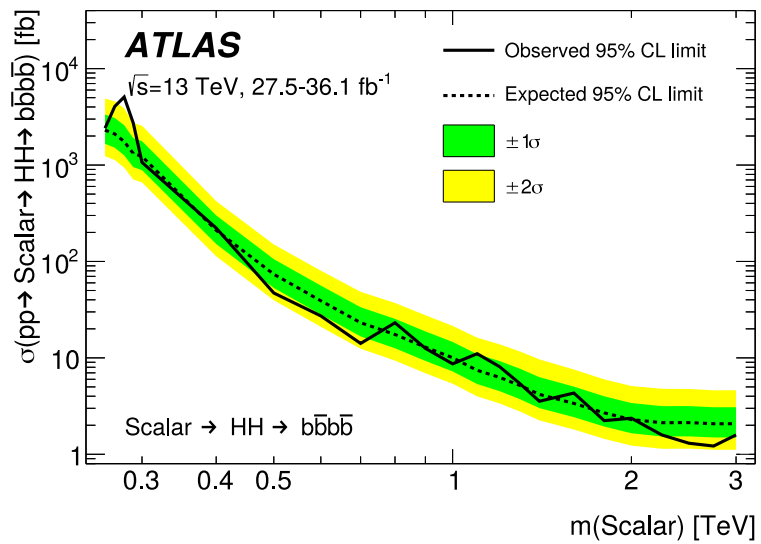


Resolved analysis, optimized for low m_{HH}:

- 4 resolved b-tagged jets, combined to 2 Higgs candidates with masses close to m_H
- Uses 27.5 fb^{-1} of data, reduced luminosity from a problem in online b-tagging

Boosted analysis

- 2 large-area jets each with ≥1 b-tagged track-jets and mass compatible with m_H.
- Full 2015+2016 dataset



Limits set for a narrow-width scalar and a spin-2 KK RS graviton model with $k/\overline{M}_{pl} = 1$ or $k/\overline{M}_{pl} = 2$.
Slight excess for scalar at 280 GeV

arXiv:1804.06174

$b\bar{b}b\bar{b}$ - CMS

3 optimized searches for different masses

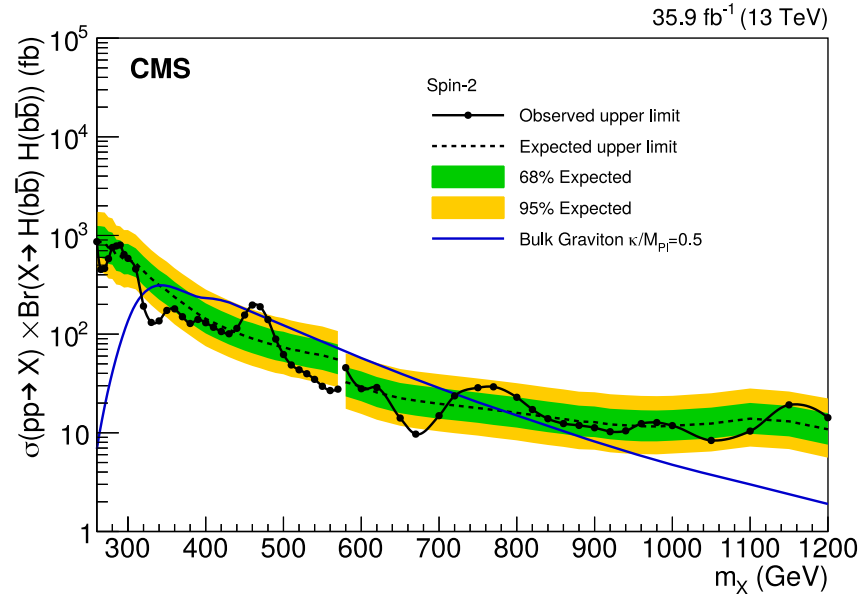
- **Low mass (M_X < 0.7 TeV)** **JHEP 08 (2018) 152**
  - 4 b-tagged jets are required
  - 2 mass regions, 260-620 and 550-1200 GeV
  - Regression techniques to improve mass resolution
- **High-mass (M_X > 1.2 TeV)** **Phys. Lett. B 781 (2018) 244**
  - 2 boosted H jets, double-b tagger
  - Jet substructure and flavor tagging techniques
  - Reduced invariant mass m_{jj} - (m_{j1} - m_H) – (m_{j2} – m_H) used for fitting
- **Intermediate mass (0.7–1.2 TeV)** **arXiv:1808.01473**
- Both fully resolved final state and the one with a H jet and two b jets

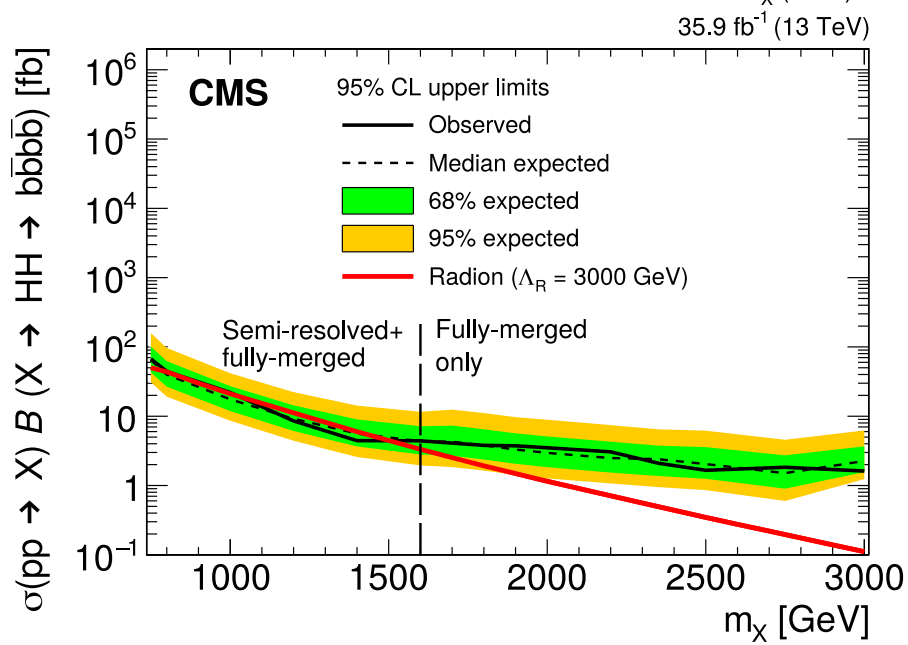
Parametric models for signal and background

Dominant background from QCD multijet events estimated using data sideband regions

Similar sensitivity as ATLAS, but better at low masses

Deficit where ATLAS sees excess





$b\bar{b}\tau\tau$ – semileptonic and fully hadronic

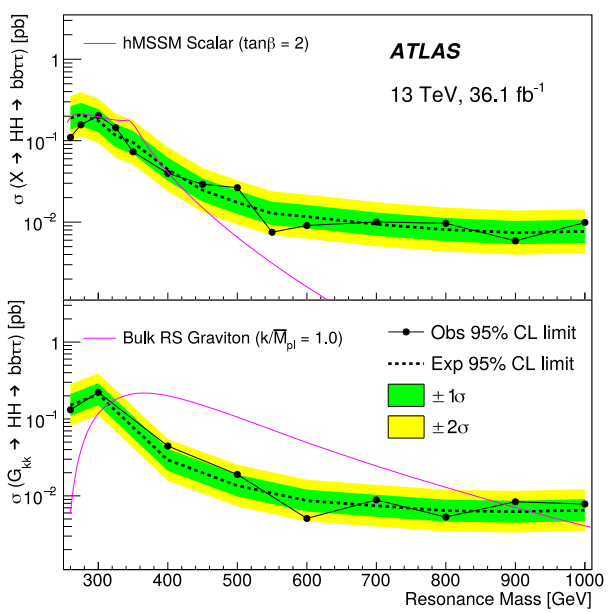
More details in A.Parker's talk

Most sensitive channel for **ATLAS for** low masses (**<400 GeV**)

- Final states of
  - 1 **e/μ** and 1 hadronic **τ**
  - OR 2 hadronic **τ** candidates
  - Together with **2 b-tagged jets** and **MET**
- **BDTs** for signal/bkg separation
- Profile-likelihood **fit** applied to the **BDT** distributions in 3 signal regions (hadronic, 2 SL with different triggers) and to event yields in a CR for Z+hf

305 < m_X < 402 GeV for tanβ = 2 excluded for hMSSM

Gravitons excluded 325 GeV < mG_{KK} < 885 GeV, assuming $k/\overline{M}_{Pl}$ = 1

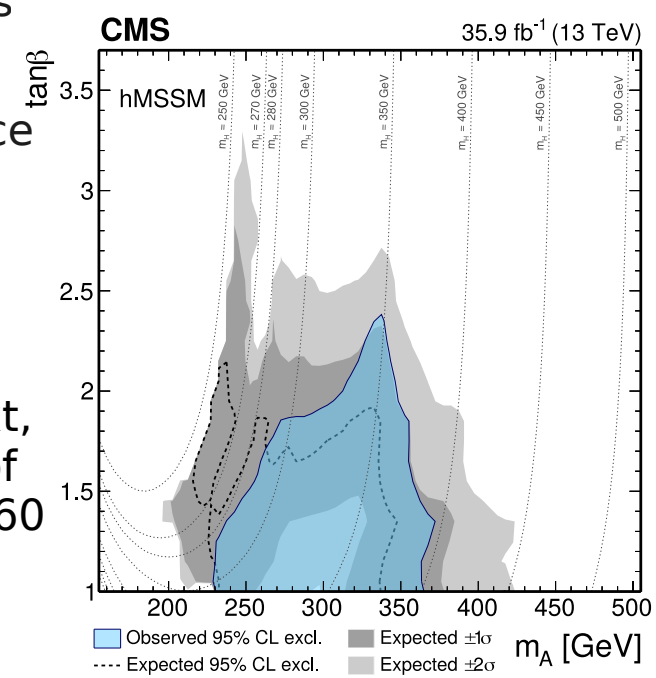


Phys. Rev. Lett. 121, 191801 (2018)

- Categories of **1 or 2 b-tagged jets**, dedicated **category** for events with a **boosted H** jet candidate
- **Selection** based on $m_{\tau\tau}$ and $m_{b\bar{b}}$
- BDT in the resolved semileptonic channels to reduce $t\bar{t}$ background
- Likelihood technique for $m_{\tau\tau}$ and kinematic fit for $m_{\tau\tau b\bar{b}}$ reconstruction
- Binned ML fit performed simultaneously in the signal regions

Limits set for narrow resonance in range 250 < m_S < 900GeV

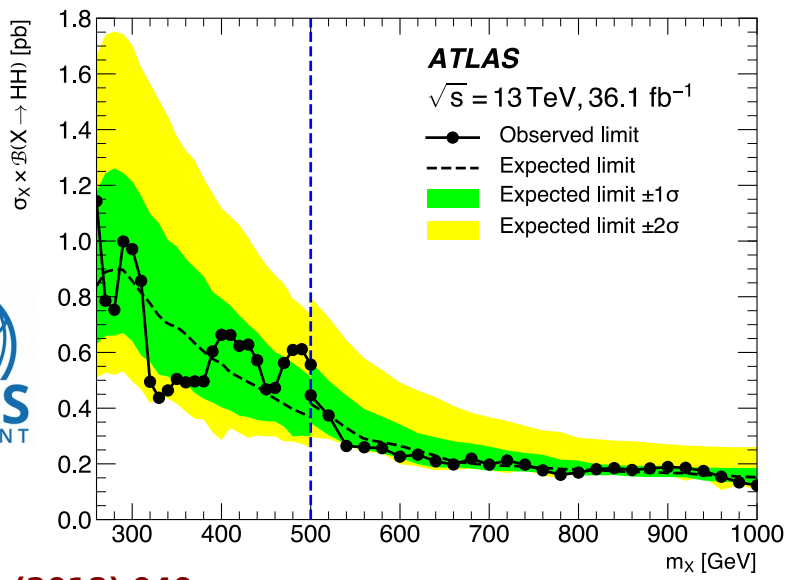
Interpreted in hMSSM context, 2D exclusion of 230 < m_A < 360 GeV and tan β ≤ 2



Phys. Lett. B 778 (2018) 101

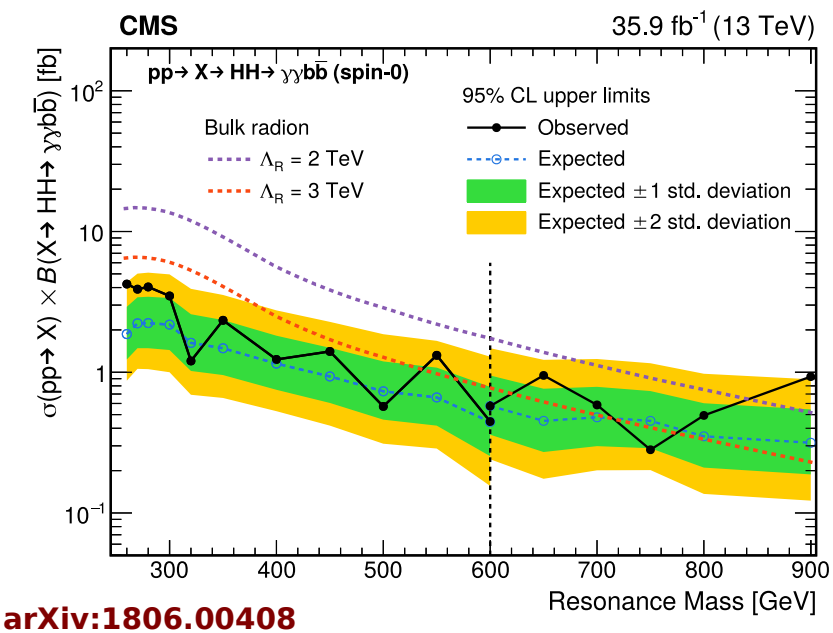
$b\bar{b}\gamma\gamma$

- Event categories with either 2 b jets or 1 tight b jet and another jet selected by BDT
- Additional **kinematical selection**, different for masses over/under 500 GeV
- **Signal** extracted **from $m_{\gamma\gamma jj}$** spectrum by fitting a peak superimposed on a smoothly changing background
  - **$m_{\gamma\gamma}$** mass required to be within 4.7(4.3) GeV of m_H
- Observed **limits** range from **1.1 to 0.12 pb** over the mass range (without branching fraction ≈0.26%)



JHEP 11 (2018) 040

- **Most sensitive** channel **in CMS** at **low masses** thanks to γγ mass resolution (≈1.6 GeV)
- **Two** different **BDTs** trained for corrected inv. mass $\widetilde{M}_X$ over/under 600 GeV, strategy maximizes the sensitivity to the massive resonances
- **2D fit of $m_{\gamma\gamma}$ and $m_{b\bar{b}}$** in categories of BDT value and $\widetilde{M}_X$ mass window, background estimated from mass sidebands.
- **Excluded** cross sections of **4.2 to 0.23 fb** depending on m_X and the spin hypothesis.
- Limits set for radion and graviton models



arXiv:1806.00408

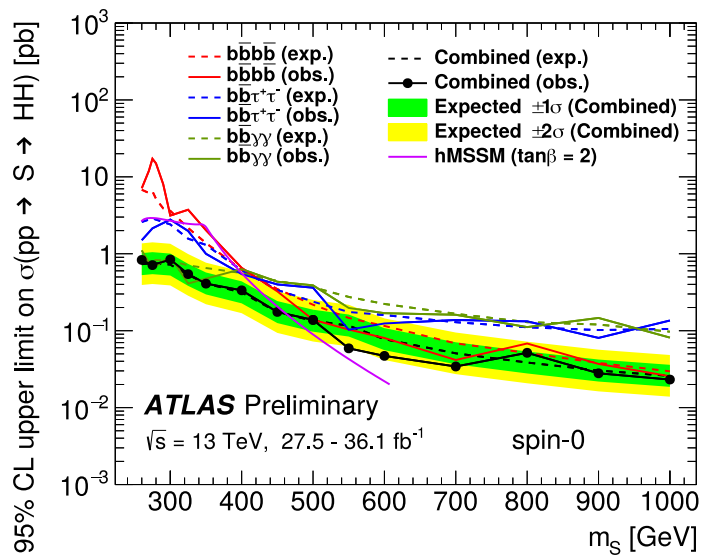
Combination

$b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$ channels

Mass range 260–1000 GeV

Limits set for:

- Heavy scalar S with narrow width: 0.83 pb – 0.02 pb
- Spin-2 KK graviton with a width of 3-25% depending on mass and $k/\overline{M}_{pl}$

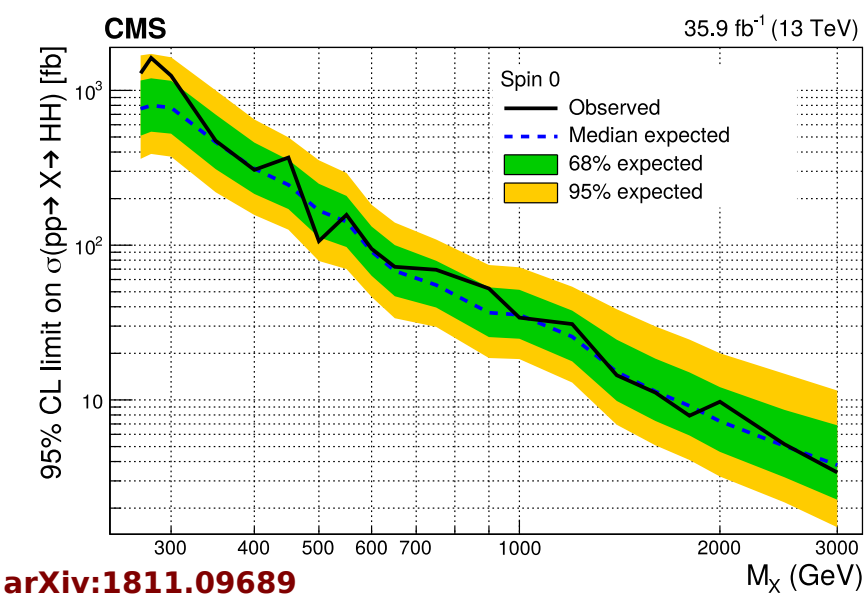


ATLAS-CONF-2018-043

$b\bar{b}b\bar{b}$, $b\bar{b}\tau\tau$, $b\bar{b}\gamma\gamma$, $b\bar{b}VV$ channels

Mass range 250-3000 GeV

Under hypothesis of a narrow-width resonance, no significant excess for either a spin-0 or a spin-2 particle



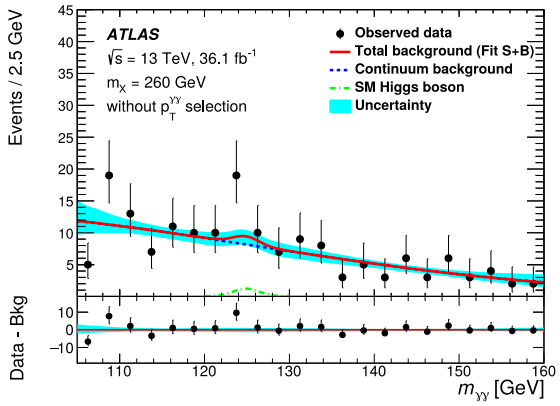
arXiv:1811.09689

Other results

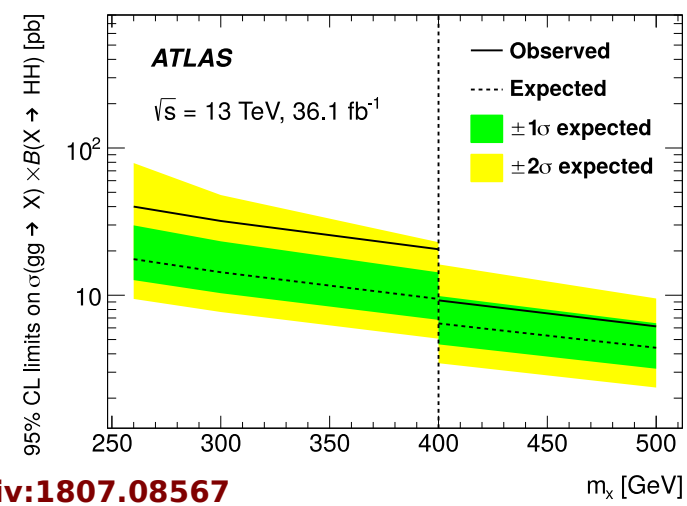
ATLAS γγWW*, WW* → lνqq

Event selection based on properties of final state objects:

- 1 e or μ
- 2 light jets
- 2 photons



Benefits from excellent resolution of $m_{\gamma\gamma}$, used to fit signal and background yields



arXiv:1807.08567

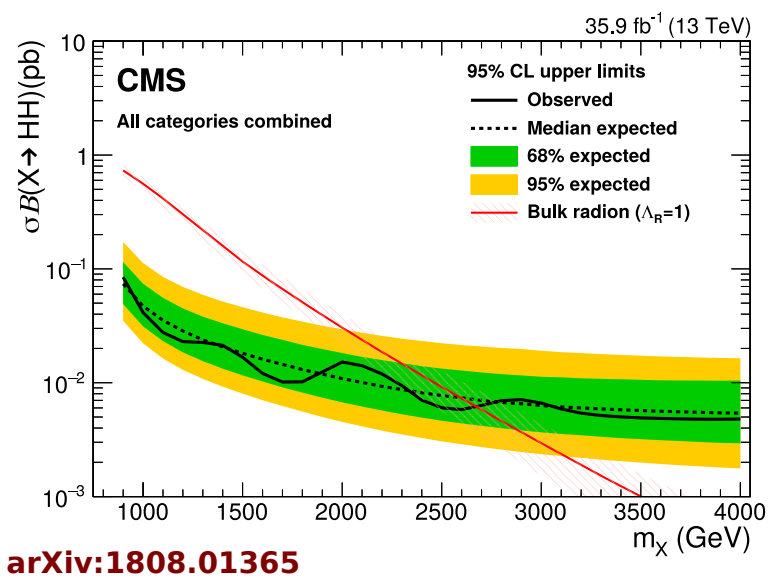
CMS high mass bbττ

Boosted large-cone jets

Dedicated H → $b\bar{b}$ tagging techniques for substructure

Reconstruction techniques specifically optimized to select events in which the tau pair is highly boosted

Results obtained from a combined fit to m_{HH} distribution

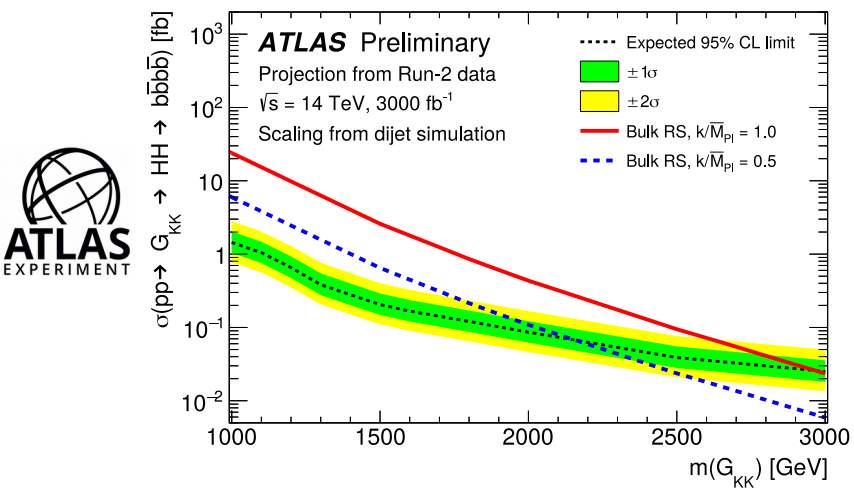


arXiv:1808.01365

Studies for HL-LHC: $b\bar{b}b\bar{b}$

Boosted analysis with large-radius jets

- Signal and background m_{HH} distributions taken from the most recent ATLAS analysis at 13 TeV, scaled to 3000 fb^{-1}
- Simulations used to derive mass-dependent scaling functions to extrapolate 13 TeV to 14 TeV
- Simulated distributions used to reproduce the impact of additional selection criteria not used at 13 TeV
- Systematic uncertainties scaled down by factors of ≥2 (where applicable) relative to 13 TeV to account for increased precision with 3000 fb^{-1}



ATL-PHYS-PUB-2018-028

CMS-PAS-FTR-16-002

Projection from 2015 bbbb analysis

- Theoretical uncertainties are scaled down by a factor ½
- Experimental systematic uncertainties are scaled down by the square root of L until lower limit based on achievable accuracy estimates with the upgraded detector
- Effects of higher pileup conditions and detector upgrades not taken into account

m_X(TeV)	Median expected limits on σ (fb) ECFA16 S2	Stat. Only	$\sigma_R^{NLO}(\Lambda_R = 1\,\text{TeV})$ (fb)	Λ_R (TeV) excluded ECFA16 S2
0.3	46	41	7130	13
0.7	7.3	3.4	584	8.9
1.0	4.4	2.4	190	6.6

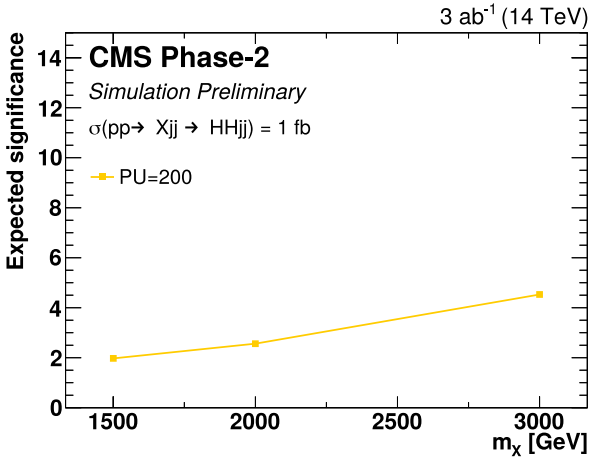
VBF analysis

pp → $Xq\bar{q}$, X→HH→$b\bar{b}b\bar{b}$:

Higgs bosons highly boosted, reconstructed as large-area jets

Two energetic jets in the forward regions of the detector

Expected significance for gravitons assuming xs of 1 fb



CMS-PAS-FTR-18-003

Conclusions

- Rich research programme to search for HH resonant production underway at ATLAS and CMS
- **Many different analyses** performed
- **No sign of New Physics** so far over a range of resonance masses **from 250 to 3000 GeV**
- **Challenging process** to observe, more data needed
- Looking forward to **results with full Run2 dataset** appearing **in the next years**
- **Analysis techniques** continuously **improving**
- **New final states to be added** to cover also smaller corners of the phase space

Questions for theorists

It would be good to agree on common theoretical models to search for with ATLAS and CMS

Are the current models useful for theorists?

If not, which models would be good to look at or add to the current ones?

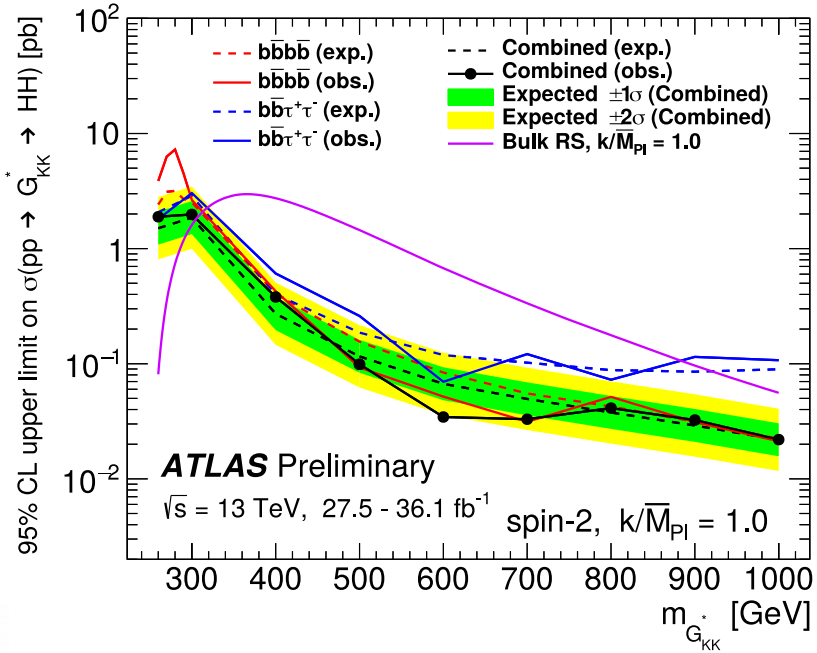
A white paper in preparation as a result of Double Higgs Production at Colliders Workshop https://indico.cern.ch/event/731450/, where this is also discussed

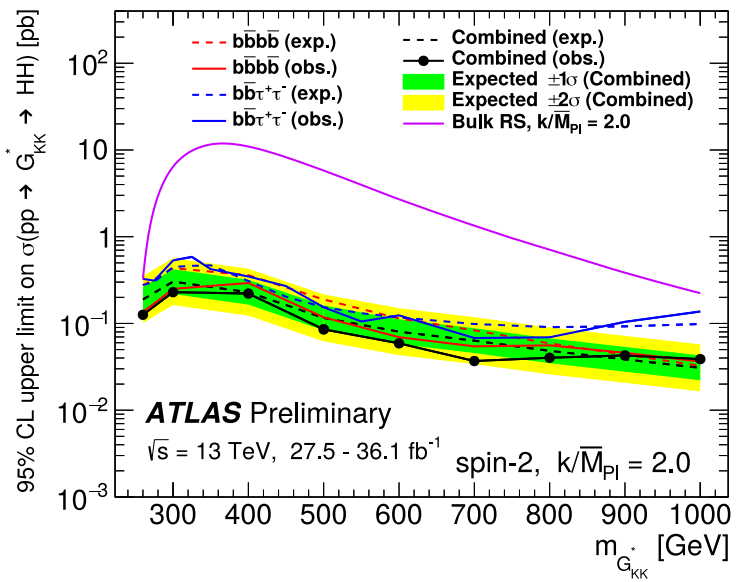
One case could be signals where there is interference between resonant and nonresonant production

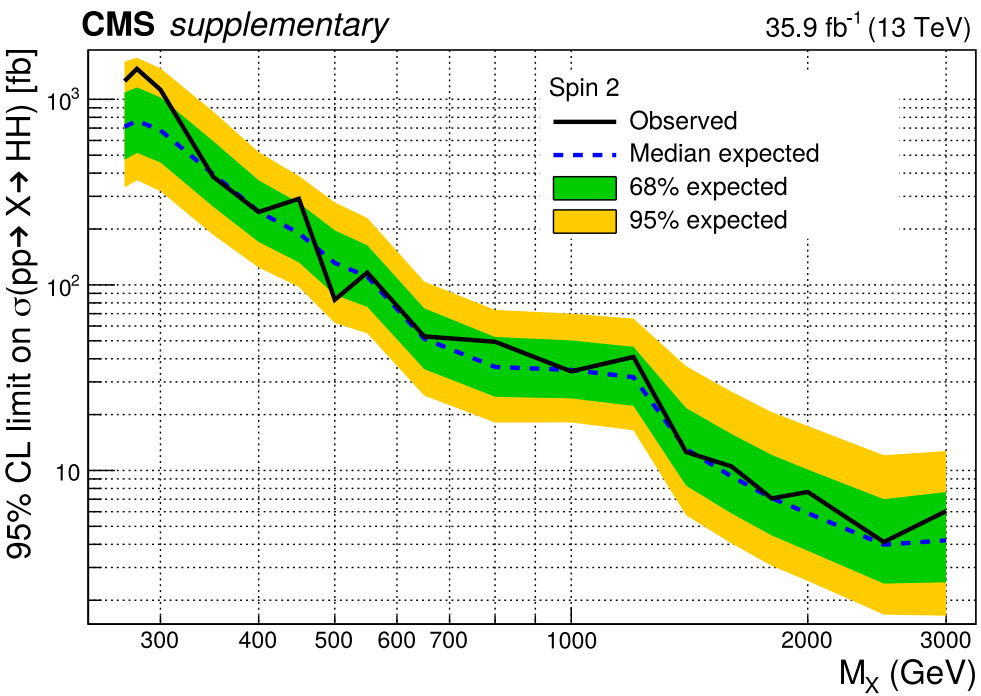
What would be good models for new heavy scalars?

Backup

Combined limits







$WW^{(*)}WW^{(*)}$ – ATLAS

In the extended Higgs sector model **X → SS** is assumed to be the **dominant X decay mode**.

Looking at masses:

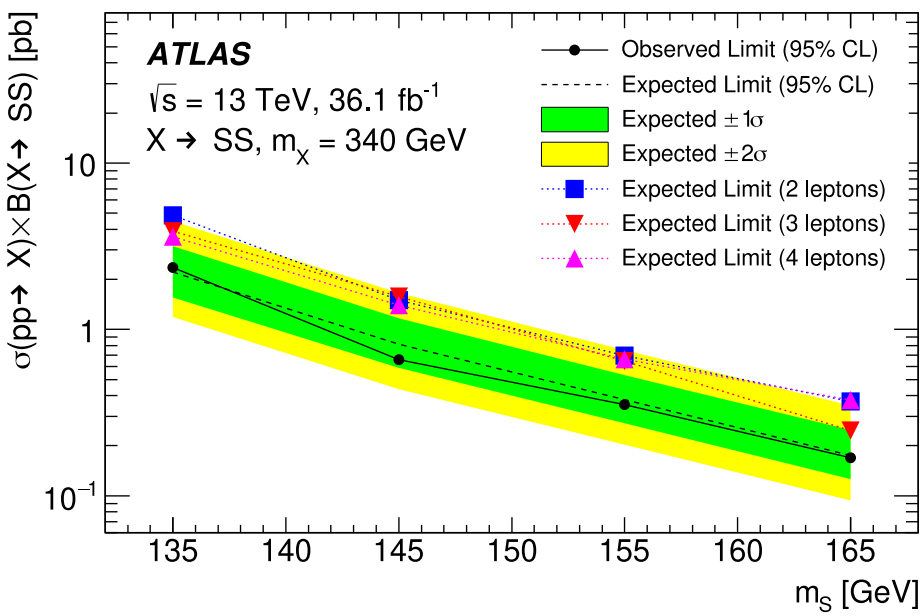
270 GeV < m_X < $2m_t$, so that:

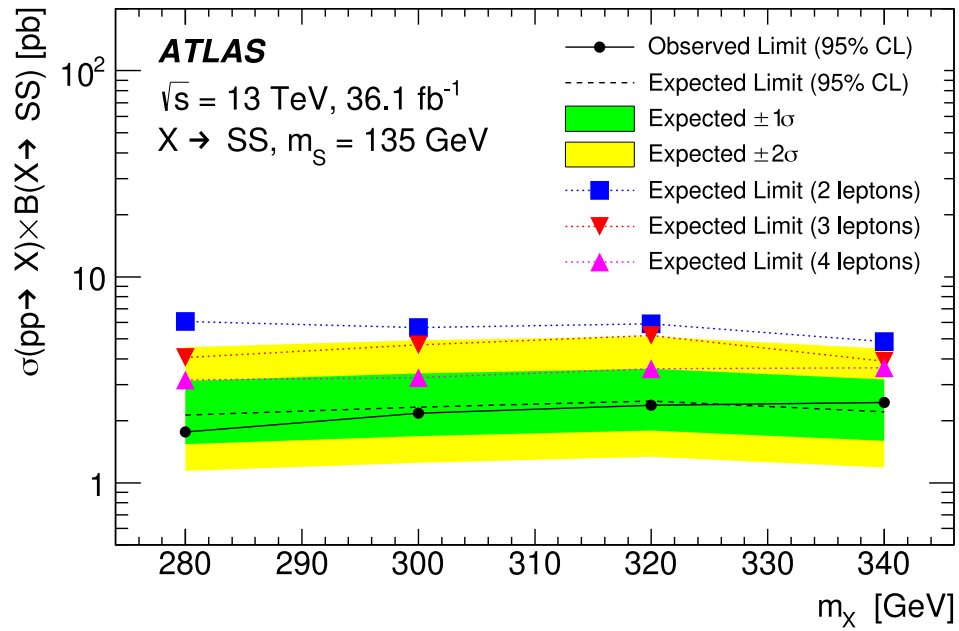
- $m_X > 2m_t$, where $X \to t\bar{t}$ is expected to dominate, is not considered

135 GeV < m_S < $m_X/2$, so that:

- $S \to WW^{(*)}$ is the dominant decay mode
- Both S bosons are produced on-shell

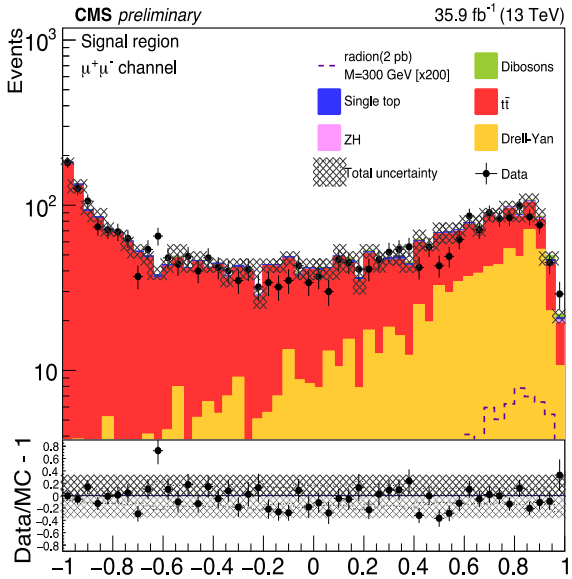
The observed (expected) limits range from **2.5 (2.5) pb to 0.16 (0.17) pb**, with the smallest limit set for m_X = 340 GeV and m_S = 165 GeV

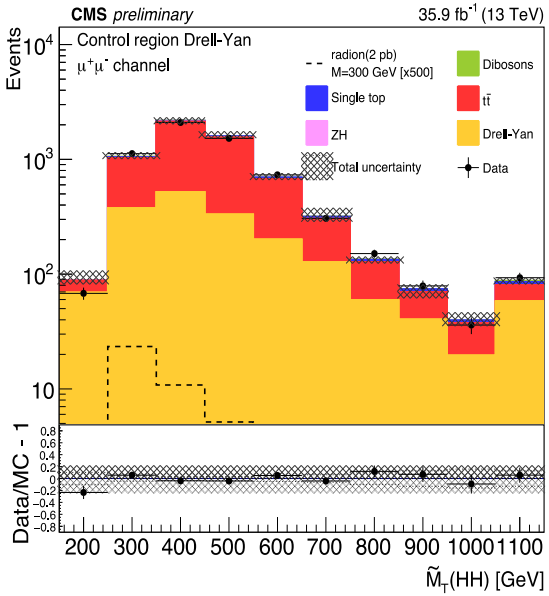


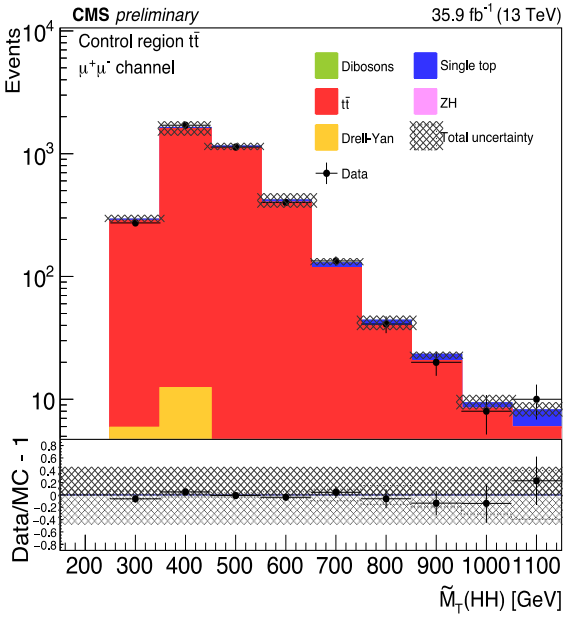


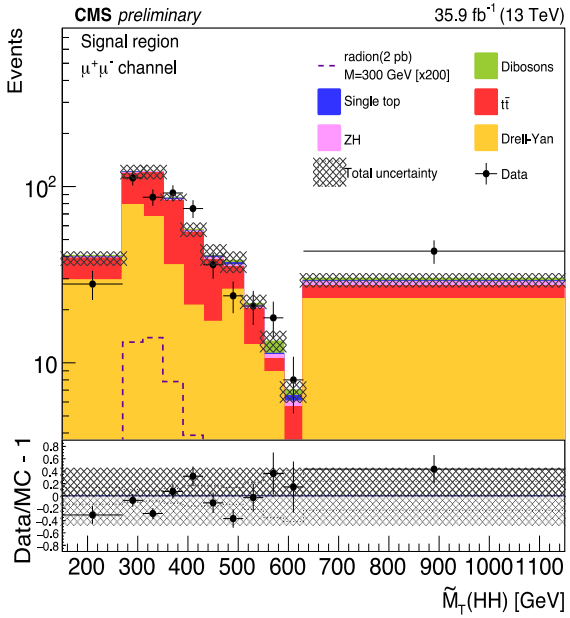
$b\bar{b}ZZ^*$ - Radion search – CMS

Radion search (spin 0),
300 GeV mass hypothesis, $\mu^+\mu^-$ channel
BDT cut is at **0.7** (in SR only)
Pseudo-M_T(HH) distributions for signal and control regions

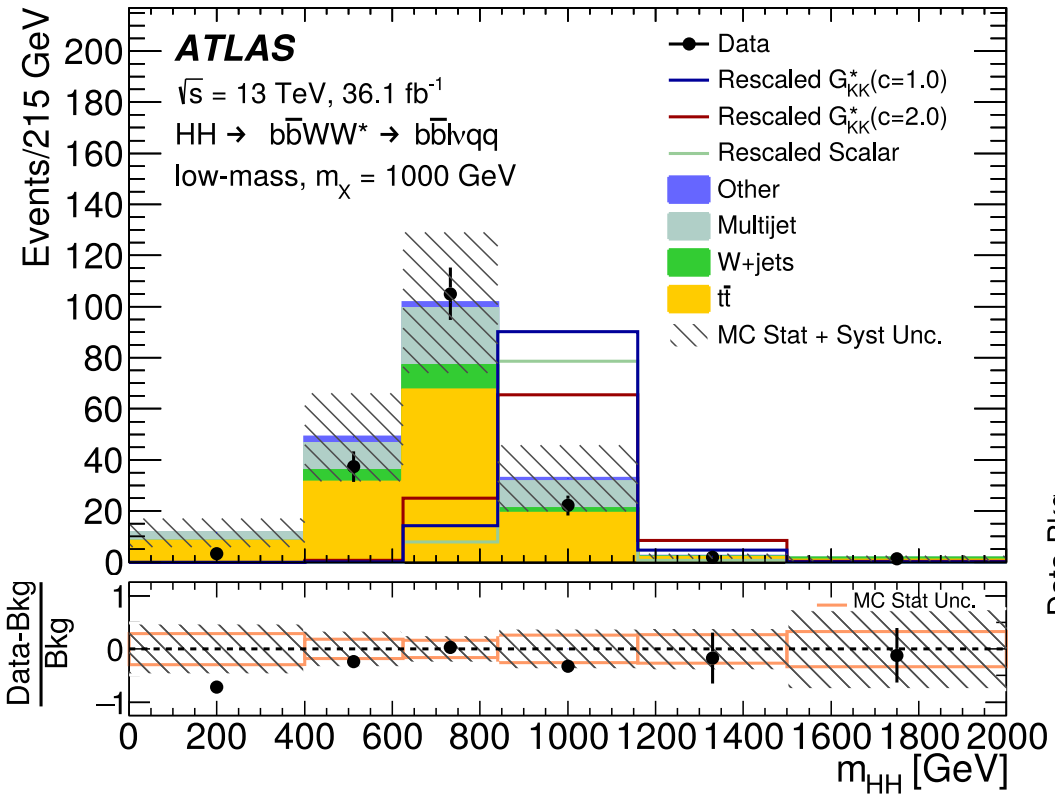


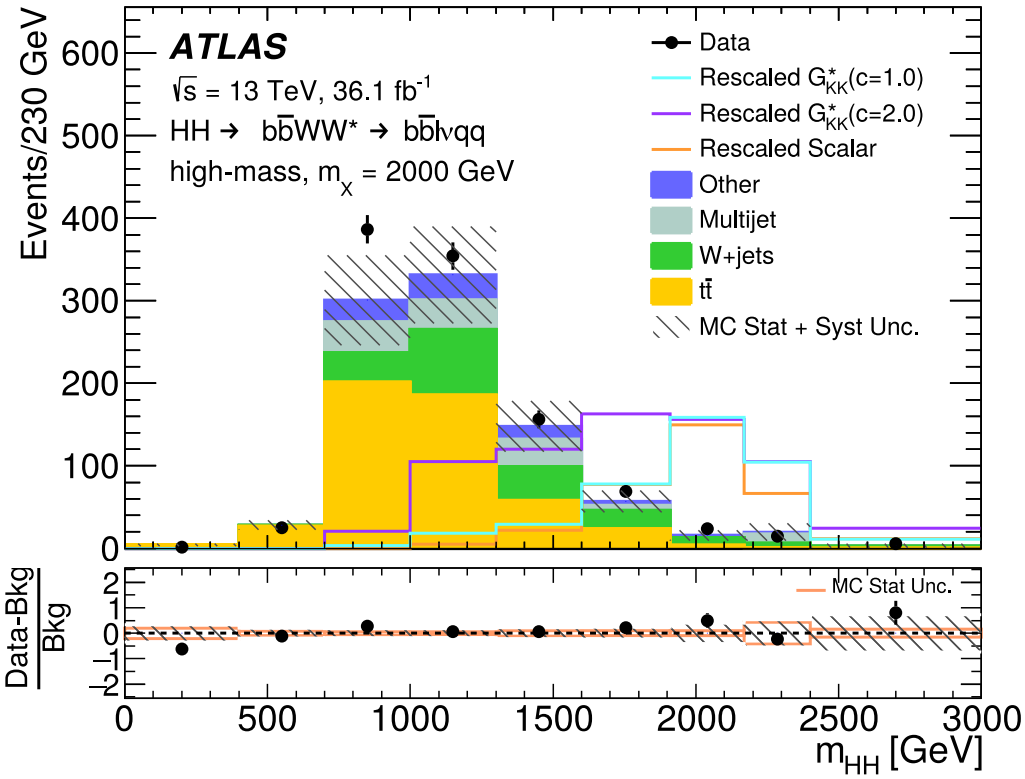




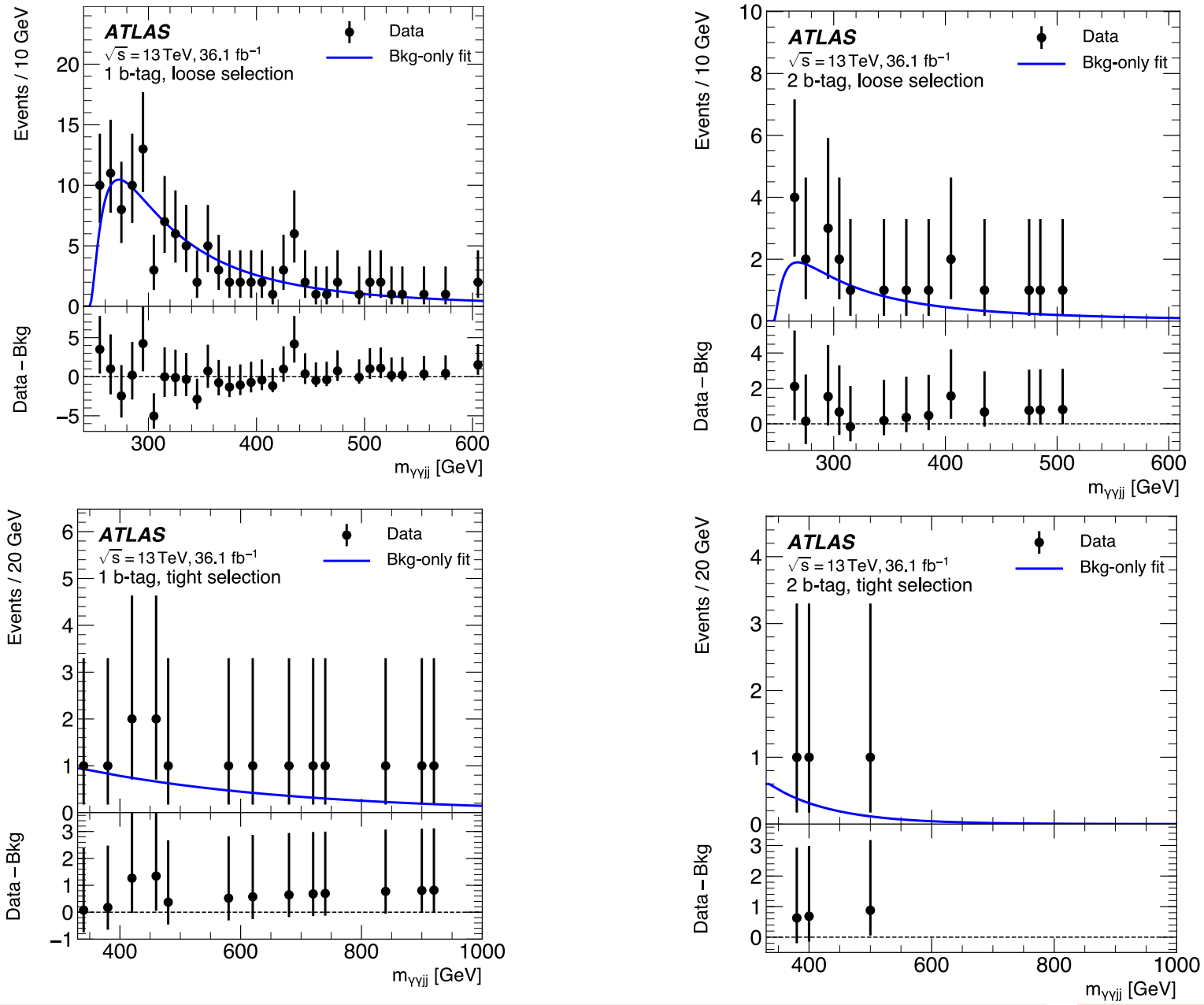


$b\bar{b}WW$ – ATLAS

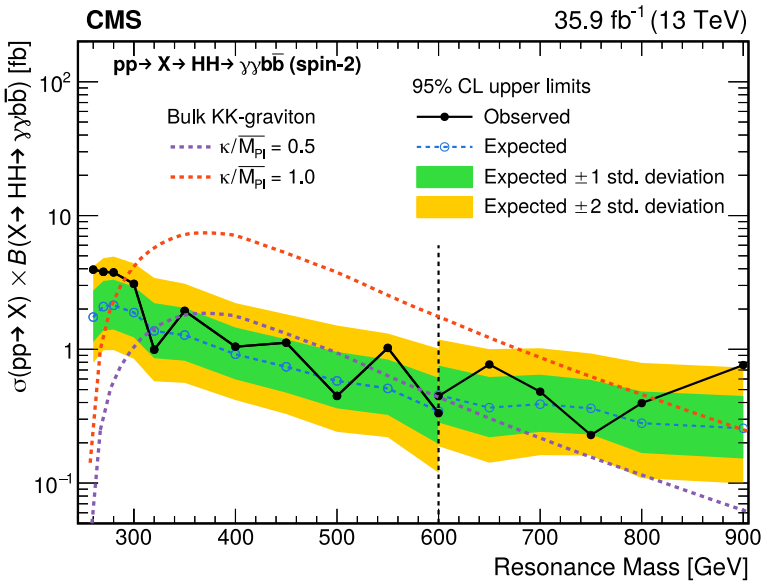


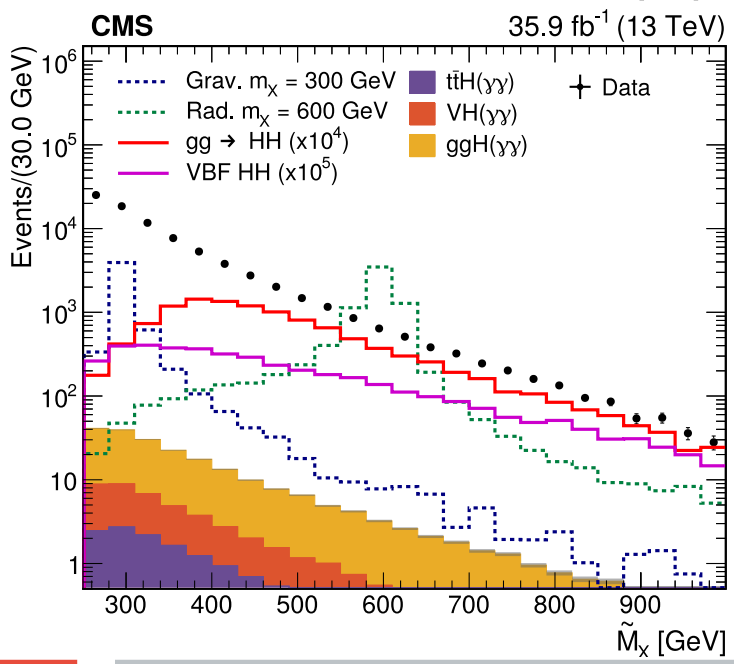


$b\bar{b}\gamma\gamma$ - ATLAS

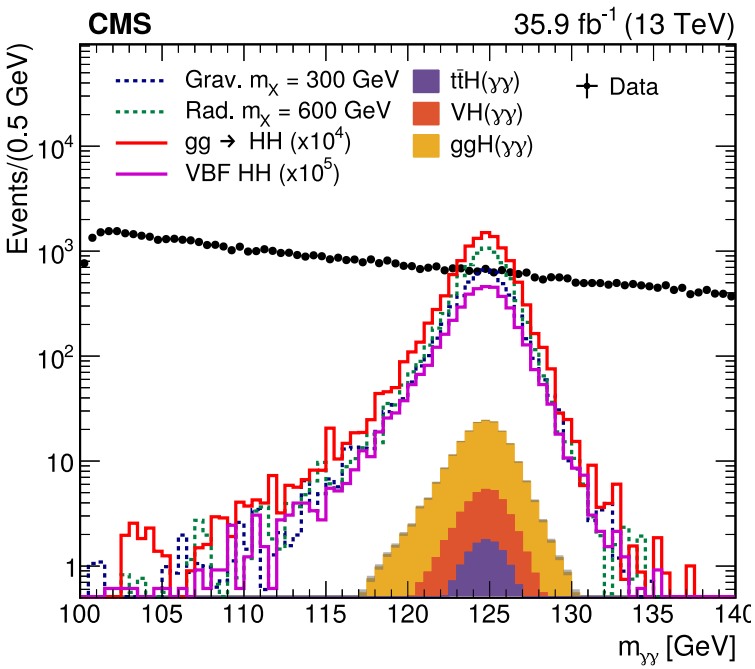


$b\bar{b}\gamma\gamma$ – CMS

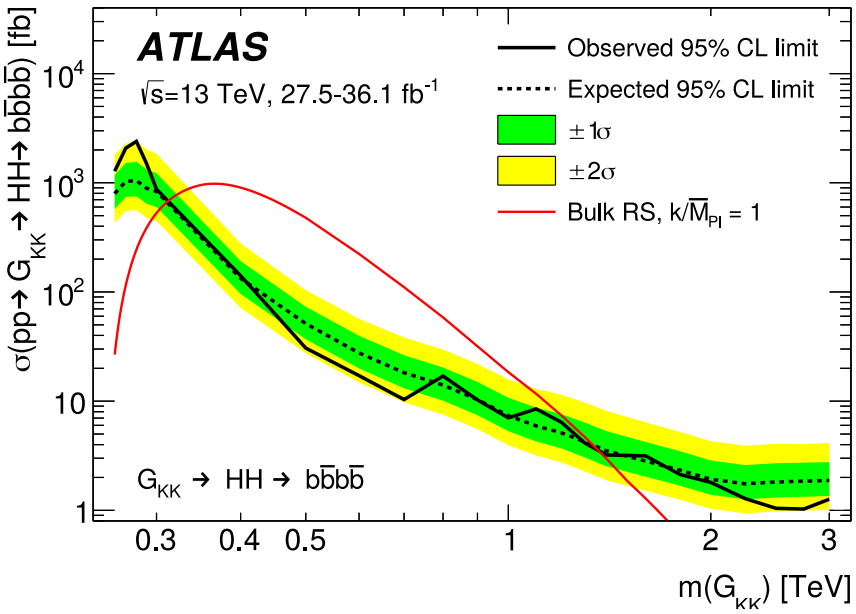


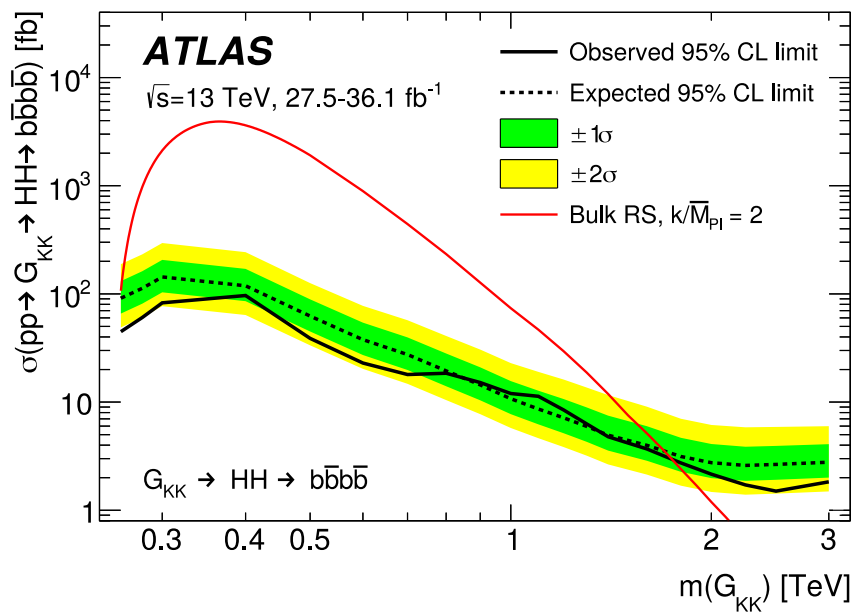


- Exclusions for radion resonances:
  - Assuming Λ_R = 2 TeV, for m_X < 840 GeV
  - Assuming Λ_R = 3 TeV, for m_X < 540 GeV.
- Exclusions for gravitons:
  - Assuming $k/\overline{M}_{pl}$ = 1.0, gravitons are excluded in the range 290 < m_X < 810GeV
  - Assuming $k/\overline{M}_{pl}$ = 0.5, the exclusion range is 350 < m_X < 530 GeV.



$b\bar{b}b\bar{b}$ – ATLAS

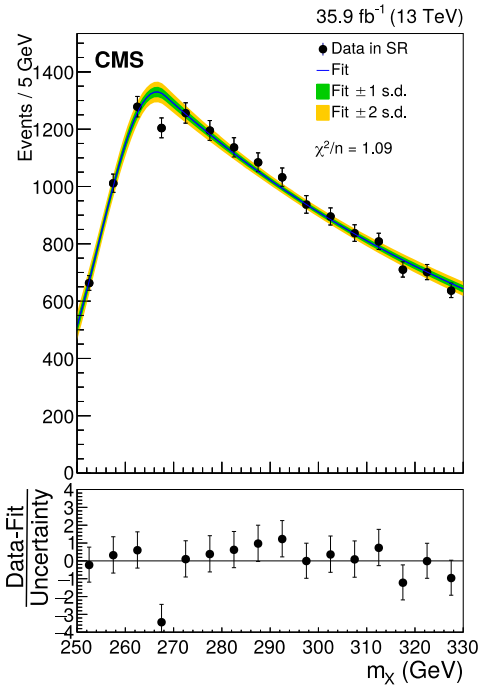


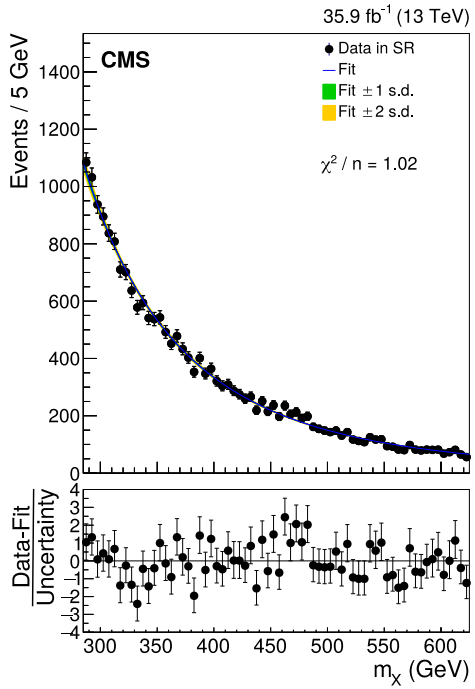


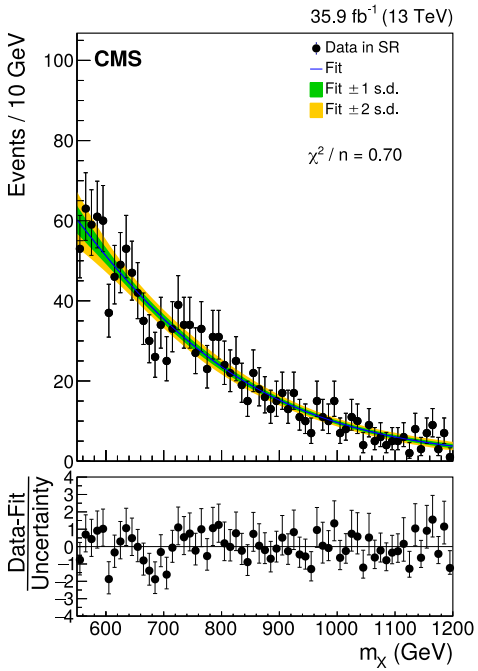
- Exclusions for bulk RS models:
  - Assuming $k/\overline{M}_{pl} = 1$, gravitons are excluded in the range $313 < m_X < 1362$ GeV
  - Assuming $k/\overline{M}_{pl} = 2$, the exclusion range is $m_X < 1744$ GeV.

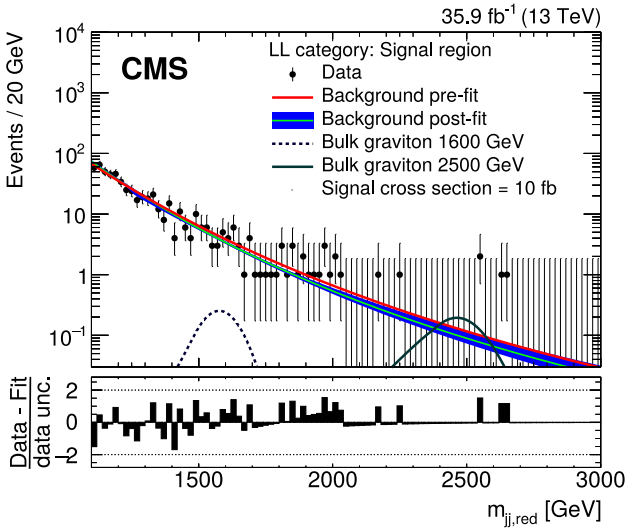
Low mass limits are stronger for the wider graviton model because in the former the signal has a larger acceptance and the distorted shape peaks at higher values of m_{4j} above a steeply falling background

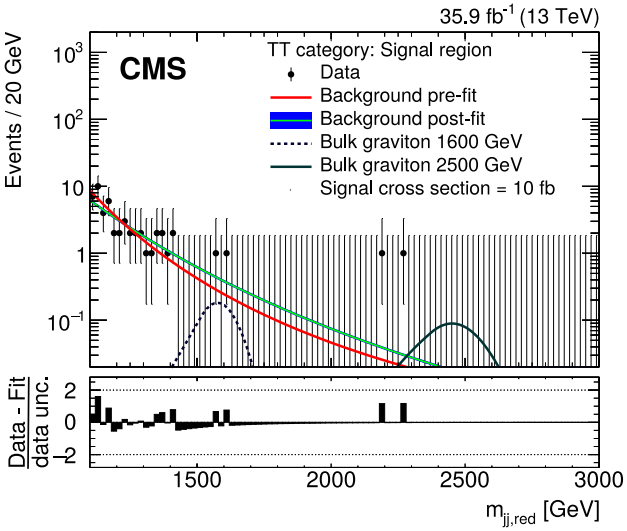
$b\bar{b}b\bar{b}$ – CMS



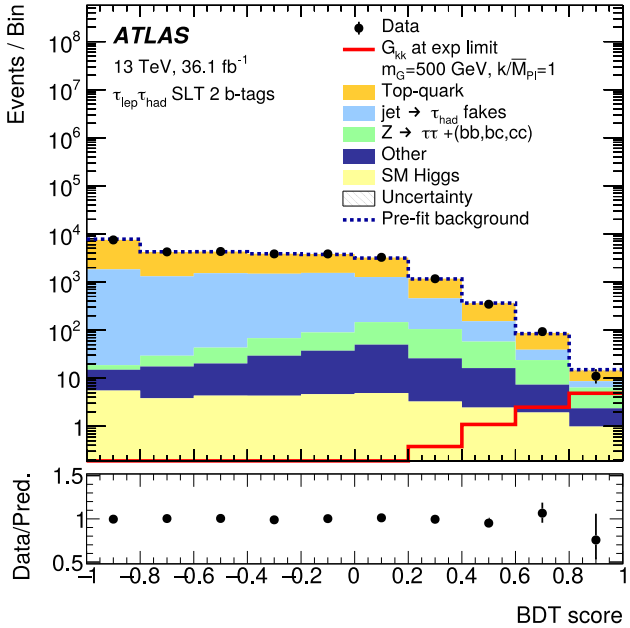


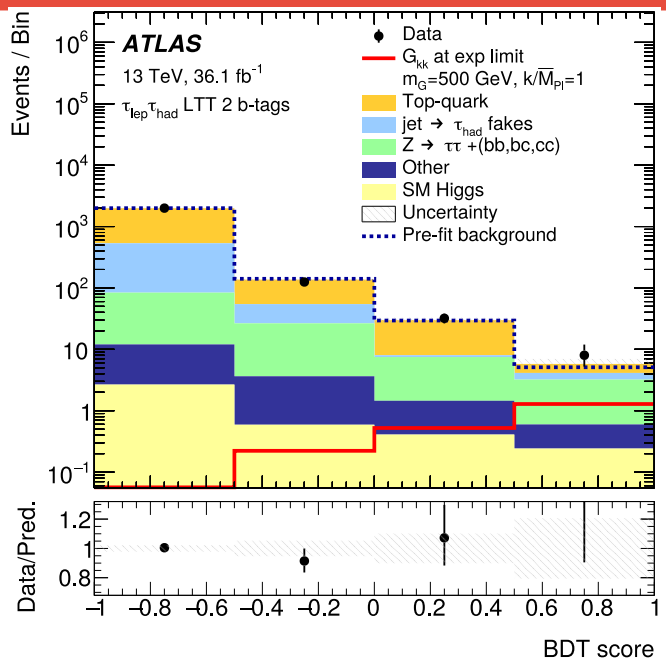


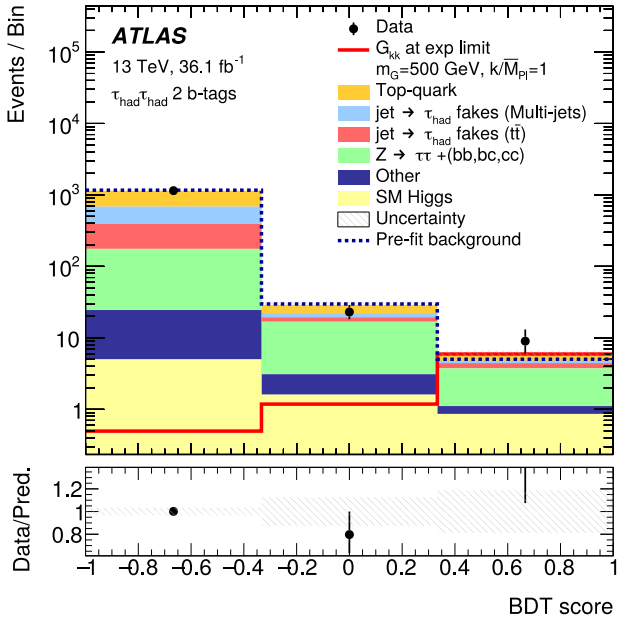




$b\bar{b}\tau\tau$ - ATLAS







$b\bar{b}\tau\tau$ - CMS